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Proportional and Integral Variable Structure Controller (PI –VSC) for Grid Connected PWM Voltage Source Converter

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ABSTRACT

This paper introduces an improved method for DC link voltage regulation in pulse width modulation rectifier (PWMR) applications. The mathematical model of PWMR in synchronous reference frame is introduced. This model is used to investigate and design of DC voltage and current control loops. The current controller is designed based on modulus optimum, magnitude optimum, (MO) criteria while the voltage controller is designed based on Proportional Integral (PI) with variable structure control (VSC) concept, which is denoted as PI-VSC. In PI-VSC, the control system switches between PI and pure I controllers according to pre-defined switching function. The PI-VSC has three tuning parameters, which are the PI-controllers gains and the switching function. The PI controller gains are tuned using Symmetrical Optimum (SO) criterion, while the switching function based on the absolute error signal. To verify the validity of the proposed controller, different simulation results are obtained under different operating conditions such as reference tracking and reference regulation at different loading condition and system parameter variation as sources of disturbances. The performance of the control system using PI-VSC is compared with the fixed structure PI controller obtained from MO and SO techniques.

Keywords: Pulse width Modulation Rectifier (PWMR), PI controller, Voltage Structure Controller (VSC), Modulus Optimum (MO), Symmetrical Optimum (SO).

1 INTRODUCTION

The AC/DC energy conversion is used in a wide area of industrial and general-purpose applications. The AC/DC conversion is done by using combination of diodes and line commutated thyristors with a large DC capacitors. Such approach draws a pulsed current from the grid which causes several problems such as, injection high harmonics into the grid and poor utilization of the grid due to high harmonics into the current and injection harmonics into near equipment's connected to the same grid [1]. Today AC/DC conversion is done using fast switching power devices as voltage source converter this AC/DC converter called pulse width modulated Rectifier (PWMR) [2]. The PWMR is presented to solve the problems of the traditional conversion system. The attractive features of PWMR are constant DC link voltage, nearly sinusoidal utility current with less harmonics, ability for bidirectional power flow and controllable power factor. The feature of bidirectional power flow is useful in case of electric braking in electric drive applications. In transmission of electric power using high voltage direct current (HVDC) [3] application and grid integration of renewable energy resources such as PV [4], wind [5, 6], and storage systems [7]. For high utilization of the PWMR a high dynamic response is needed this leads to many research focusing on the control of PWMR. The most common one used is Voltage Oriented Control (VOC) technique which originates from the field oriented control (FOC) of the induction motor [8]. Another methods such as direct power control can be applied[2]. Proportional derivative controller with type two fuzzy neural network (PD-T2FNN) is proposed in [9]. The control is very complex. Analyses, design methods and the performance of the voltage and current proportional integral (PI) controllers, which are as usually made up of inner current control loops and an outer voltage control loop in a cascade structure [10]. The PI controller in the current control loop is tuned with Magnitude optimum (MO), criterion the PI Controller in the voltage control loop is tuned using Symmetrical optimum (SO) criterion [11]. In [12], the PI of current loop is designated using zero pole cancelation and the gain is set to achieve closed loop cut-off frequency 10 times greater than the open loop . On the other hand, the voltage controller is deigned to achieve critical damping operation. In [10], approximated the system with first order and time delay after that applied nonlinear optimization methodology to optimize the controllers gains. Quasi optimum voltage and current controllers are designed to optimize the integral time absolute of error (ITAE). Application of meta-heuristic technique to optimize the voltage and current controllers concurrently have been applied in [13]. The controller's parameters and structure

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are fixed.

In this paper the PI controller in current control loop is tuned using MO and kept fixed while the voltage controller is modified to operate on the concept of VSC according to the system operating condition. The resulting controller called PI-VSC. In [14 and 15] the controller switched between P or I only one controller at a time. In this paper the P controller is left to operates contentiously while I controller is get in and get out based on the absolute value of error. When the error is too large P controller operate, while when the error reduced to predefined value. The integral controller is imposed on the proportional controller to eliminate the steady state error. Different disturbance and system parameter variations are applied on the system to see the validity of the proposed controller.

The paper is arranged as follow, Section II gives the system description with mathematical modeling of PWMR. Section III introduces the tuning techniques for PI and PI-VSC. Section IV shows the simulation results for both controllers (PI and PI-VSC) under different operating conditions. Section V provides a conclusion about using PI-VSC.

2 SYSTEM DESCRIPTION

Fig.1 shows the schematic diagram of PWMR based voltage source converter connected to grid. The converter control aims to regulate the dc linkage voltage by maintaining balance between the dc link power and ac power with controllable reactive power. For that the standard VOC technique is used which gives a decouple control of active and reactive power. For the analysis and control design the basic system equations which describing the system dynamics is presented based on analysis done in [8]. The phase voltage and current equation are given by equation (1).

$$e_{abc} = Ri_{abc} + L\frac{di_{abc}}{dt} + v_{abc} \tag{1}$$

Where: $e_{abc}, i_{abc}, and\ v_{abc}$ and are the ac voltage, current and converter voltage respectively. R and L are the resistance and filter inductance between the converter and ac source respectively. In VOC the converter 3-phase current and voltage equations are transformed into dq 2-axis synchronous reference frame rotating at ac supply frequency ω. The converter voltage equations in qd reference frame given by equations (2) and (3).

$$e_d = Ri_d + L\frac{di_d}{dt} - \omega i_q + v_d \tag{2}$$

$$e_q = Ri_q + L\frac{di_q}{dt} + \omega i_d + v_q \tag{3}$$

Where: d and q are subscripts refer to the direct and quadrate axis components respectively.

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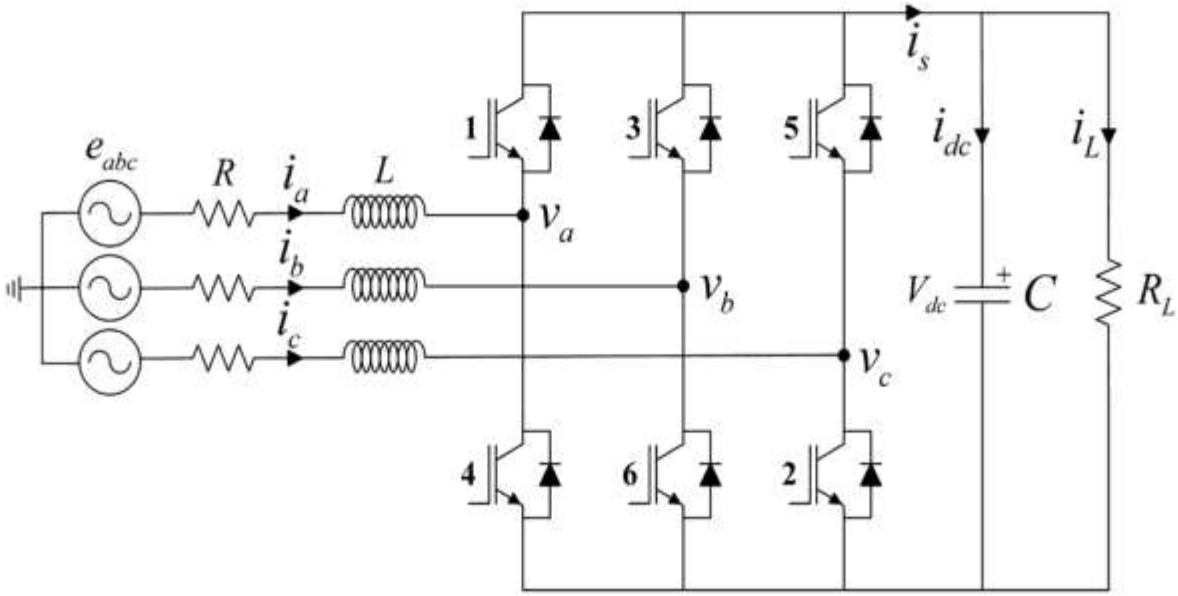

Figure 1 PWM grid connected VSC [9]

If the converter losses are neglected, the power balance equation between the ac and dc link given by equation (4).

$$P = \frac{3}{2}\left(e_d i_d + e_q i_q\right) = v_{dc} i_s \quad (4)$$

The reactive power can be determined using equation (5)

$$Q = \frac{3}{2}\left(e_q i_d - e_d i_q\right) \quad (5)$$

Where v_{dc} and i_s are the dc link voltage and current respectively. The dc current as function of capacitor and load current is determined using equation (6).

$$i_s = c\frac{dv_{dc}}{dt} + i_l \quad (6)$$

If the d-axis of rotating reference frame is aligned to the ac supply voltage vector then, with this alignment the instantaneous active and reactive power transfer between the converter and ac supply are given by equation (7) and (8) respectively.

$$P = \frac{3}{2} e_d i_d \quad (7)$$

$$Q = -\frac{3}{2} e_d i_q \quad (8)$$

Therefore, the active power is controlled by the d-axis current component and reactive power is controlled by the q-axis current component. Fig.2 shows the system model with the control. The controller is implemented using PI controller where inner current control loops for controlling in active and reactive power and an outer voltage control loop in cascaded structure.

3 CONTROLLER TUNING

From figure 2, the control system of PWMR contains three controllers two of them to regulate the current components for active and reactive power control. The third one is the dc voltage regulation controller which is in cascade with active current components controller. The controllers are considered independent where the dc voltage controller provide the reference current signal for active current control and the current controller provide the suitable signal to generate the switching pattern of the PWMR as shown in figure 3. The current controllers are tuned using MO method as simple and straight forward method, while the voltage controller use a combination between SO and VSC concept. In the following sub section steps for both techniques are given

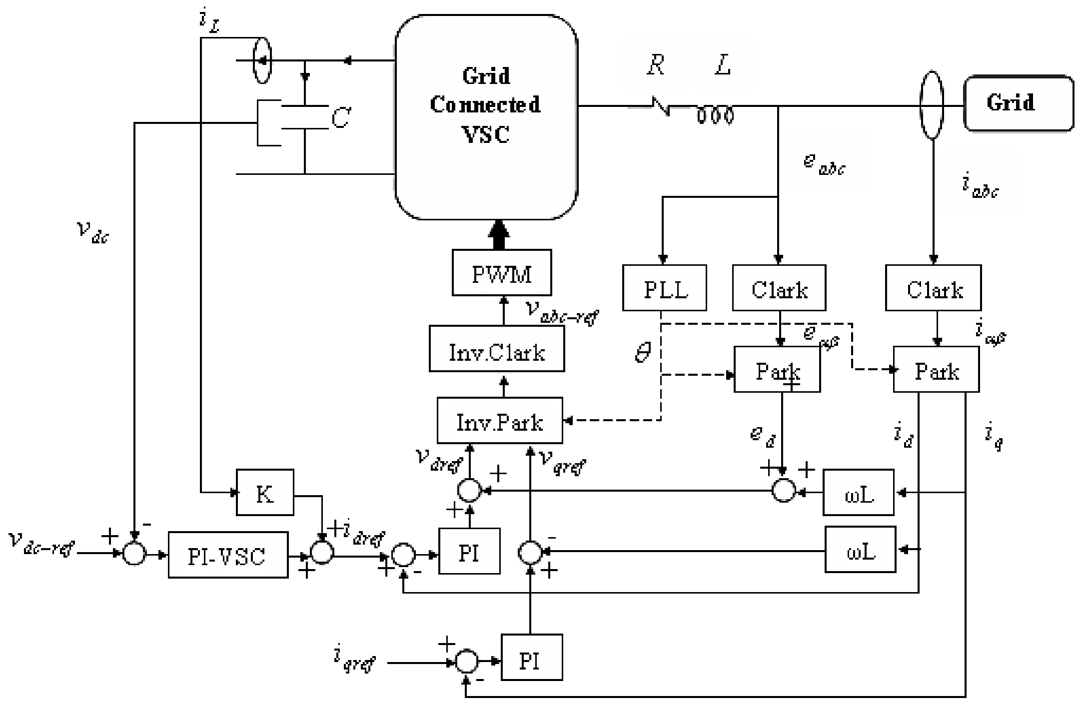

Figure 2 VOC control of PWMR with load current compensation

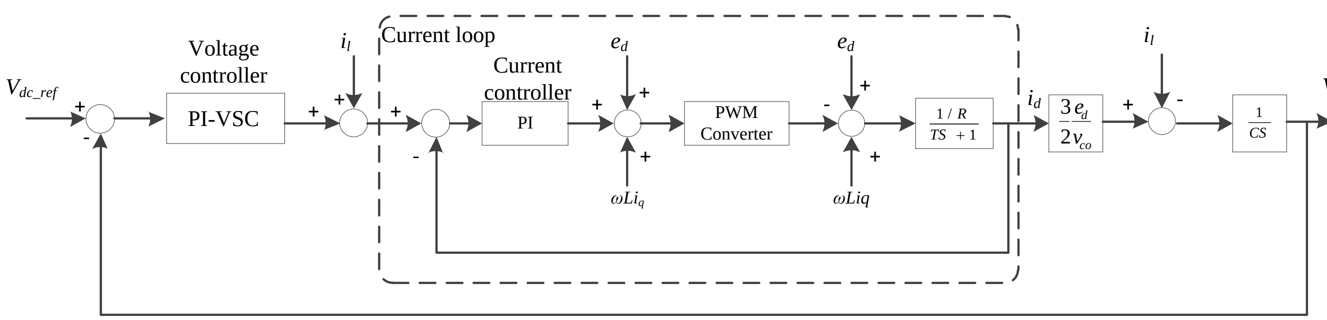

Figure 3 voltage and current control loops

3.1 Current controller tuning using MO

The PWMR control system contains two loops for current components. The two loops are identical so that the controller is designed for one and the same is used for the other. Fig.4 shows the current control loop. The loop contains two times constant one for the converter and the other for the line connect the PWMR to the grid. As the converter operates at high switching frequency then the control loop has one dominant time constant corresponding to the grid line. For the systems with one dominant time constant and no poles at the origin in s plane the PI controller is commonly tuned using MO for its simplicity and faster response. In MO the zero of PI controller is adjusted to cancel the dominant pole of the system while the gain is adjusted to keeping the magnitude of transfer function equal to unity for a wide range of frequency as possible this leads to faster response. The same results can be obtained by letting the damping ration of the closed loop system equal to $1/\sqrt{2}$. Then the controller parameters will be given by equations (9) to (12). Hence, the resultant current closed loop transfer function given by equation (13).

$$T = \frac{L}{R} \tag{9}$$

$$T_{con} = 1.5T_s \tag{10}$$

$$T_{ii} = T \tag{11}$$

$$K_{ii} = \frac{R}{2T_{con}} \tag{12}$$

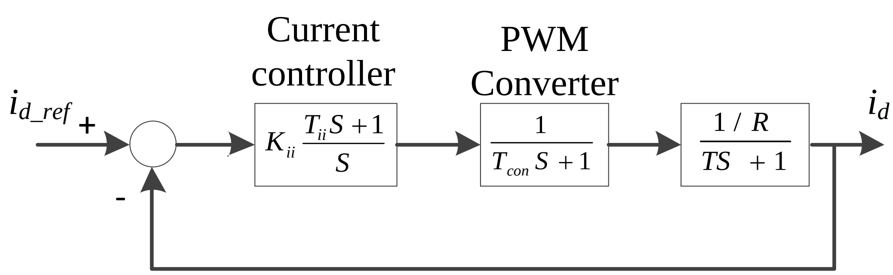

Figure 4 Simplified current control loop

$$G(s) = \frac{\frac{K_{ii}}{RT_{con}}}{S^2+\frac{1}{T_{con}}S+\frac{K_{ii}}{RT_{con}}} \tag{13}$$

3.2 DC voltage controller tuning using PIVSC without sliding mode

The proposed voltage controller is discontinues PI controller operates on the concept of VSC without sliding mode. Fig.4 shows the proposed dc voltage controller. Such approach uses continuous and discontinuous modes of operation. The idea of changing the controller structure depends upon the location of the system trajectory in the state space. The PI-VSC consists of a proportional (P) control

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part, represented by gain Kp, and integral (I) control part, represented by gain KI. In[15] the controller switched between P or I only one controller at a time. In this paper the P controller is left to operates consciously while I controller is get in and get out based on the absolute value of error (ϵ). When the error is too large P controller operate only, while when the error reduced to predefined value the I controller super imposed on the p controller to eliminate the steady state error and the voltage controller is like conventional PI controller .The best response of the system depends on the chosen values of Kpv, Kiv, and ϵ. The tuning of this controller passes in two phases. Phase1 chooses the controllers gains Kpv and Kiv . Phase 2 choose the value of at which switching of I controller occurs. In phase 1 the controller gains can be obtained using any suitable optimization technique or suitable traditional tuning method. As the voltage control loop contains pure integrator represent the charging part of capacitor the MO or zero pole cancellation is not suitable so another method most used in tuning continues PI controller which is SO.

3.2.1 Phase 1: Tuning of PI dc voltage controller using symmetrical optimum (SO) criteria

For simplification the design of the voltage controller the inner loop of current control is approximated by first order as shown in Fig.5 with . Since the system has pure integrator the PI tuning using zero pole cancellation isn't suitable as it leads to two poles at the origin and the system become unstable. In this case the PI tuning using SO is more suitable. The SO is obtained from Nyquist criteria of stability in which the controller parameters are adjust for maximizing the phase margin of the open loop transfer function at certain frequency. Also SO criteria optimize the control system behavior with respect to disturbance input. The controller parameters according to SO is calculated using equations

$$\boldsymbol{a_v = \sqrt{\frac{1+\sin\emptyset_m}{1-\sin\emptyset_m}}} \tag{14}$$

$$\boldsymbol{T_{iv} = a_v T_{eq}} \tag{15}$$

$$\boldsymbol{k_{iv} = \frac{1}{a_v T_{eq} T_{iv} K_v}} \tag{16}$$

$$\boldsymbol{k_v = \frac{3e_d}{3Cv_{dc}}} \tag{17}$$

Where ϕ_m is the required maximum phase margin, T_{iv} is the integrating time constant of PI controller. The proportional gain is calculated to satisfy unity gain at maximum phase margin. The phase margin indicates the damping ratio in time domain. as the phase margin increases the system become less over shoot but the ability for disturbance rejection decrease, while the low value of maximum phase margin the over shoot increase and the ability for disturbance rejection is improved

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so that the choice of the phase margin from the control view point is comparative between the two performances[8]. In this paper 65 phase margin is used

3.2.2 Phase 2: choice the value of for I controller switching

The integrating part of PI-VSC is switched at specified value of the absolute error signal. The value of this error affects the system performance so that should be selected to give satisfied performance. The switching control law is given by (18) and (19).

$$\boldsymbol{e = \left|V_{dc\_ref} - V_{dc}\right|} \tag{18}$$

$$\boldsymbol{controller\ is\ \begin{cases} P - controller & for\ |e| > \varepsilon \\ PI - controller & for\ |e| \leq \varepsilon \end{cases}} \tag{19}$$

The procedure which may be used to determine the value of ε is listed as the following.

1. Simulate the system with P controller only with gain obtained from symmetrical optimum and record the error signal e_p.
2. Simulate the system again but with PI controller with gains obtained from symmetrical optimum and record the error e_{PI}.
3. Select the switched value ε using one of the following methods:

i- Obtain the intersection between e_p and e_{PI} and let ε be a value around it.

ii- Choose the steady-state error when only K_{pv} is used and let ε more than this value.

iii- Use trail-and-error around the two values obtained in i & ii

In this paper the selected value of ε is 50 volt.

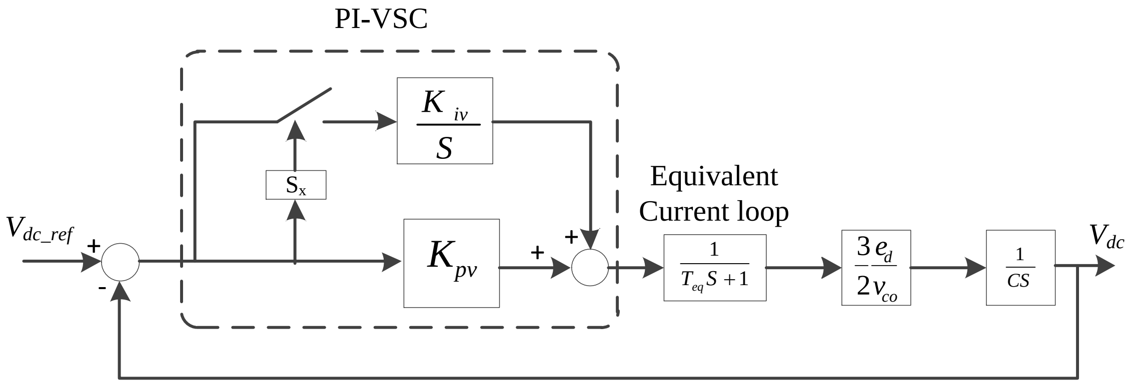

Figure 5 simplified dc voltage control loop with PI-VSC

4 SIMULATION RESULTS

The simulations are carried out on MATLAB/SIMULINK plate form for different operating conditions including suddenly applied load with and without system parameters variation.

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4.1 Case1: Reference tracing at no-load

Reference voltage tracking is suitable for applications of photo voltaic (PV) to generate electricity for solar energy with maximum power point tracking (MPPT). The simulation results for reference tracking are shown in Fig. 6 for nominal parameters value and Fig. 7 with parameter variation as a disturbance. Both controllers PI and PI-VSC provide satisfied performance while PI-VSC provides less over shoot.

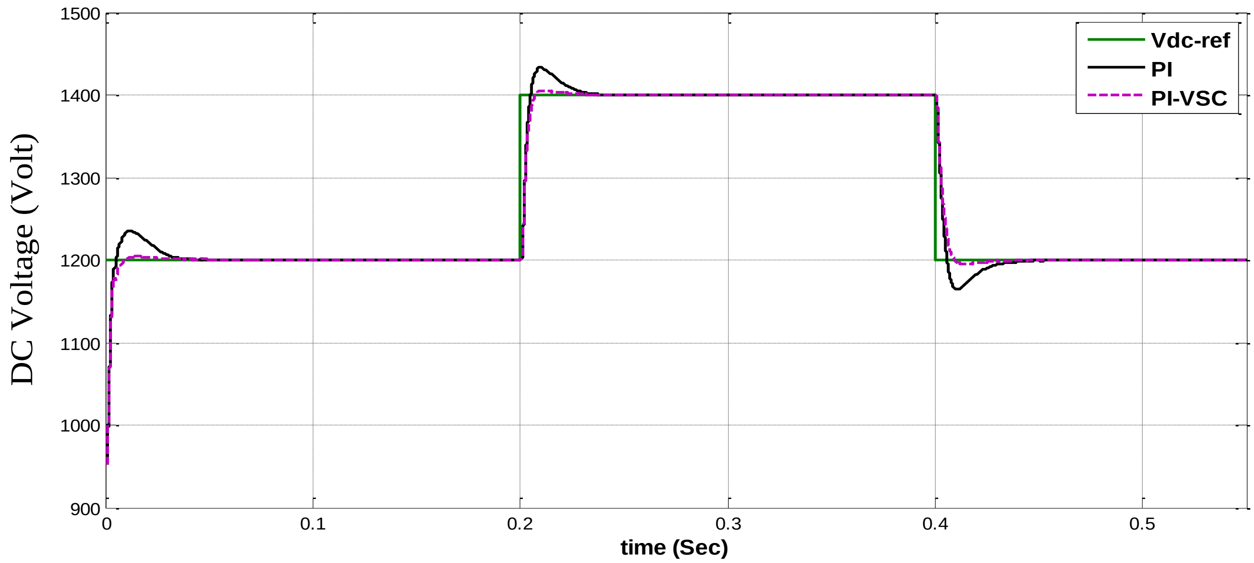

Figure 6 Reference DC voltage tracking at no load. (a) With nominal system parameters

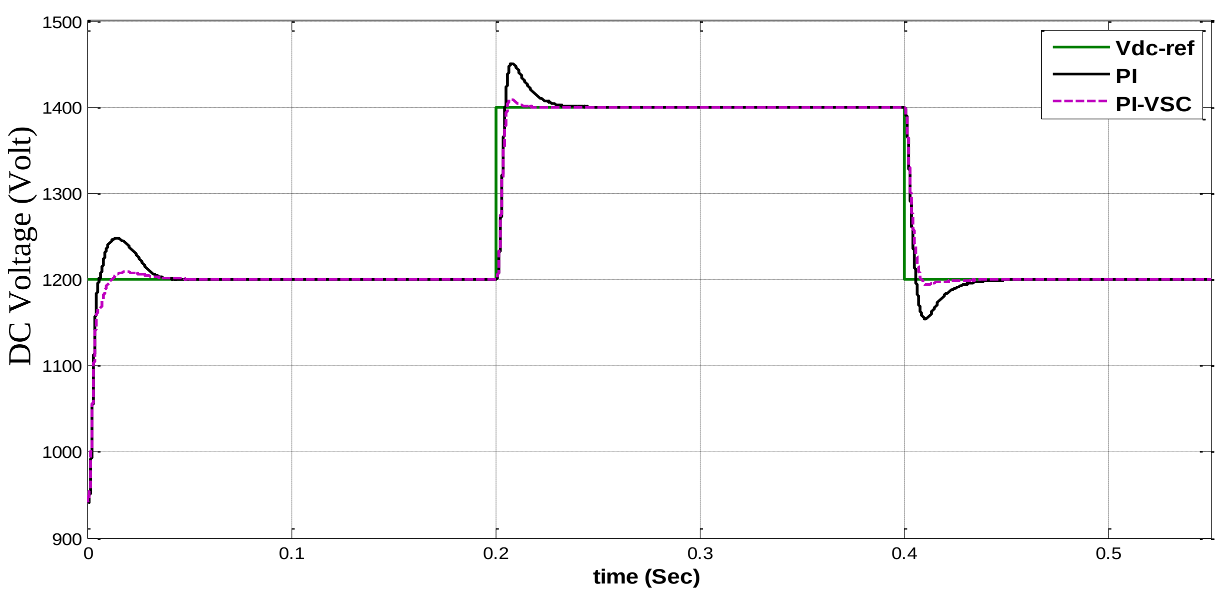

Figure 7 Reference dc voltage tracking at no load with system parameter variation.

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4.2 Case2 Reference tracking with full load

Reference tracking ability for PI and PI-VSC is shown in Fig. 8 at nominal parameters and Fig. 9 with parameter variation with nominal system parameters at full power operation (the load considered renewable energy source and modeled as power step at 0.1 sec). Both system dynamics are satisfied with PI and PI-VSC. While with parameters variation the PI controller provides poor performance but the performance under PI-VSC is better and faster.

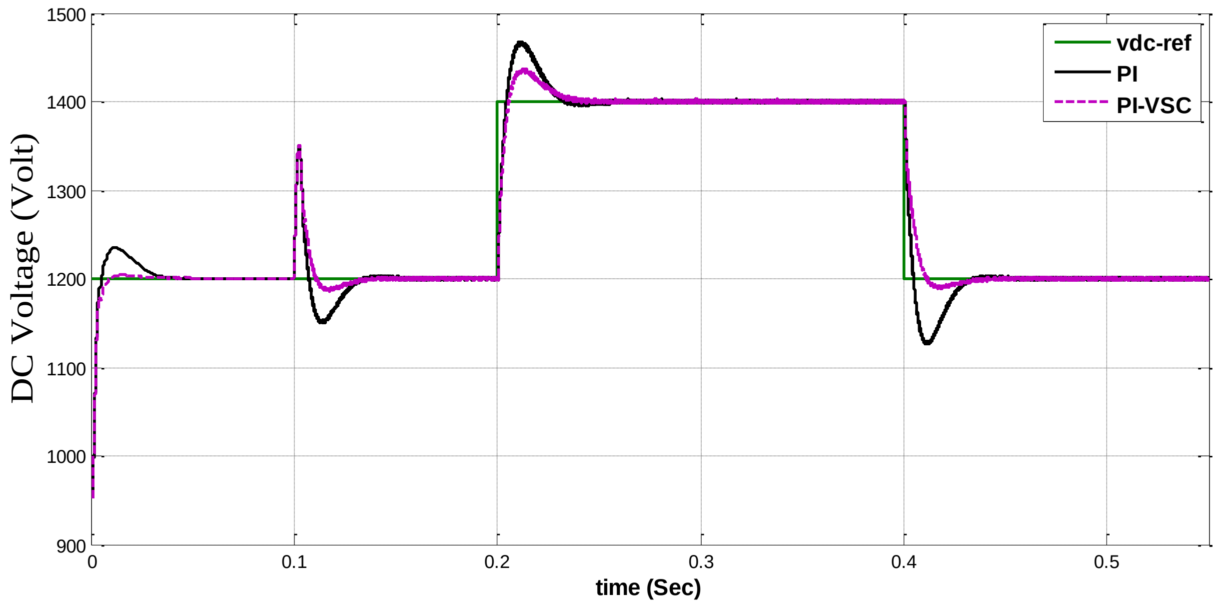

Figure 8 Reference DC voltage tracking at full load. With nominal system parameters

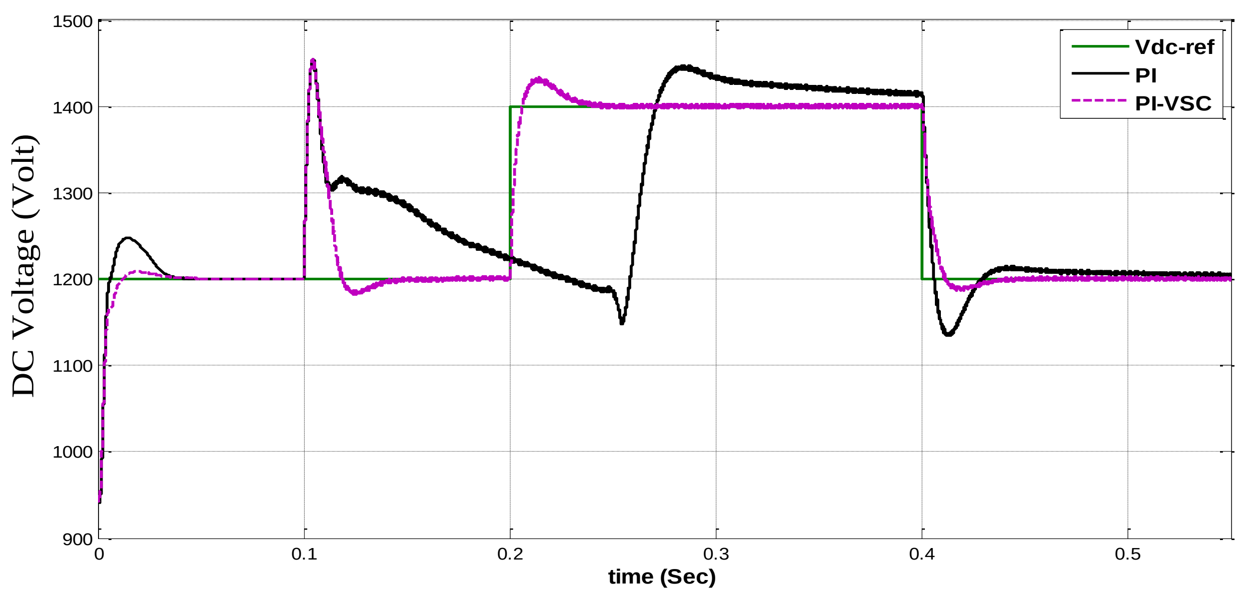

Figure 9 Reference DC voltage tracking at full load with system parameter variation.

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4.3 Case3 Reference regulation with full power

Reference regulation more used in applications of Static Var Compensator (STATCOM), wind energy applications, and electric drive applications. Fig. 10 and Fig. 11 show the ability for reference regulation for control systems at with/without parameter variation at full load when operates with renewable energy source. The PI-VSC offers better and faster response than conventional PI controller.

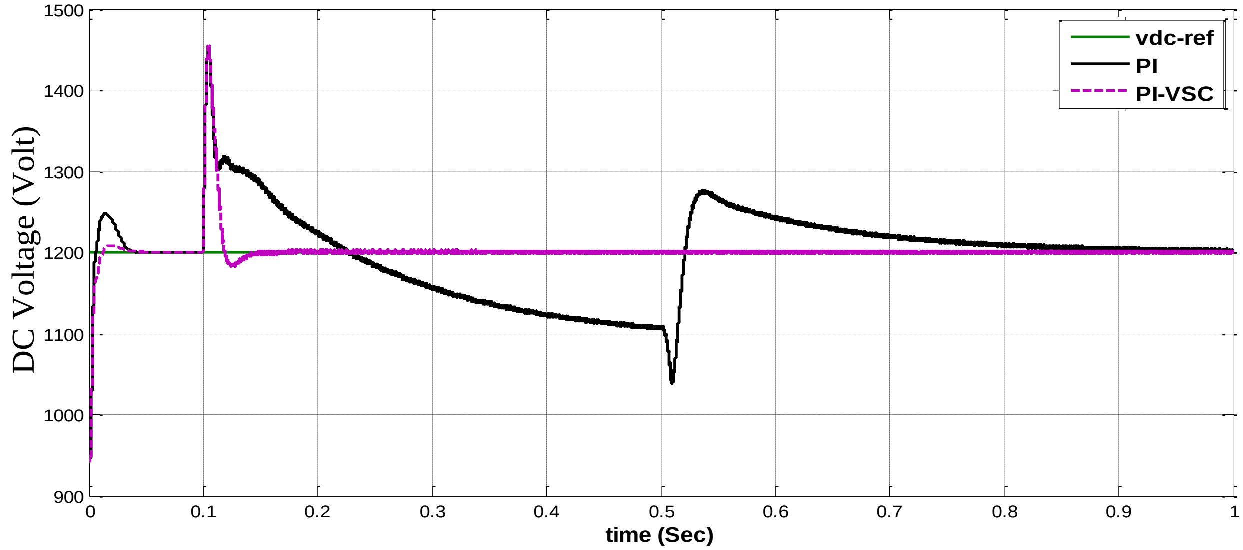

Figure 10 Reference DC voltage regulations at full load with system parameter variation

5 CONCLUSION

From the simulation results can see that in case of nominal parameters the conventional PI and PI-VSC provide satisfied performance with light improvement in case of PI-VSC. In the case of parameter variation, the controlled system performance with PI-VSC conventional has superior response compared to conventional PI controller.

APPENDIX

System parameters	
Grid line voltage	690 volt
Grid frequency	50 Hz
Converter power rating	660 kw
Dc link voltage	1200 volt
Switching frequency	5 kHz
Modulation technique	SVPWM
Dc link Capacitance	5000 µF
Nominal filter inductance	0.65 mH
Nominal filter resistance	0.005Ω
Filter inductance for parameter variation	1.114 mH

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Controller gains	
K_{pi}	1.0833
k_{ii}	8.333
K_{pv}	2.6234
k_{iv}	214.89
ε	50 volt

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